P-REx -
the Pistondrift Reconstruction Experiment

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team:

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MICADO

Science driver and goals

- IF sensitivity is driven by coherence time (piston stability)
- 8m class NIR facilities fringe track down to ~10mag regime
  - Chris and Mike can do it on paper down to 14mag…
- Nearby, bright guide stars can help but
  - Serious limitation for extragalactic applications and fainter or more rare stars (microquasars, brown dwarves …)
- Explore algorithms and technologies to derive piston variation information from AO data in combination with vibration suppression techniques
  - Pushing the fringe tracking limits is useful for VLTI as for all IF arrays
  - First candidates are L-band interferometers

Piston reconstruction experiment

- Guide star sky coverage increases typical >= 2x/Δmag, and is a much higher concern towards the Galactic poles, ie. for extra-galactic targets
  - There is essentially no quasar with a 10^m star within 20arcsec

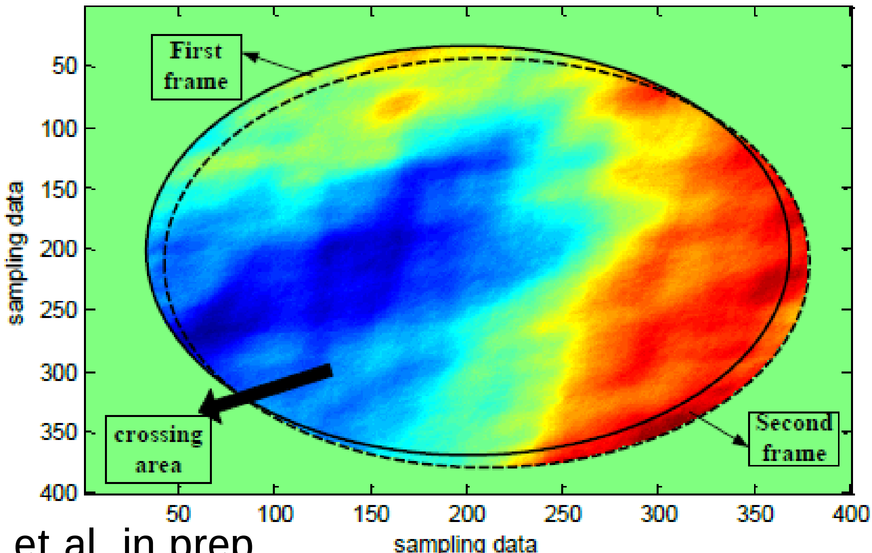
- Interferometer co-phasing limit is given by several issues
  - Facility throughput (optimized by coating and optical design, well advanced)
  - Detector readnoise (optimized by detector and electronics, now in photon counting regime)
  - Telescope vibrations (still dominant, but slowly getting under control)
  - Atmospheric coherence time (fundamental limit)

- Optimizing throughput and detector readnoise is state of the art
  - eAPDs (Opticon co-development) used in GRAVITY for instance

- We concentrate on telescope vibrations and atmospheric piston variation, **to increase the system coherence time**

PRex technology: atmosphere

- We have single-conjugate adaptive optics to flatten the wavefront (get good fringe contrast)
- We explore the real-time use of AO data to predict the **atmospheric piston time evolution**
- IDEA: **measure the effective wind speed** under the frozen atmosphere model by 2d cross-correlation of the reconstructed phase screen to **follow piston drifts** over aperture
- First simulations with a multi-layer atmo-sphere model are promising
  - Ground layer is dominating
  - We don't need to do tomographic reconstruction, but can use effective (altiude collapsed) tiptilts



Fu, Pott et al. in prep

PRex technology: atmosphere

- Real life caveats
  - Piston neutral AO operation: piston is not seen by the wave front sensor, so piston-free AO-closed loop is not necessarily given
    - Solvable in times of MOAO (ie. DM operation in feedforward)

  - Separate atmosphere from telescope phase error in real-time
    - Fast link (1kHz) between AO-WFS, vibration measurement, control algorithm and piston actuator

  - Learn from PSF reconstruction problems
    - PSF reconstruct works, but relies critically on optical alignment of the telescope, noise filtering etc
    - PREx is easier, relies on the reconstruction of the average tiptilt modes, no higher order

P-REx Simulations with YAO
(YAO: Rigaut+13)

Wind determination
Piston reconstruction
Main Parameters
Multilayer
SCAO, GLAO, & MCAO
Conclusion

Checked for dependency on:

- Wavelength
- Guide star magnitude
- Time (above 10 ms)
- Wind velocity
- Atmosphere (D/r_0)
- Sampling of WFS

TO DO: error estimation

Single layer atmosphere: limited by wind estimation

Table 1. Properties of the AO system for general tests.

Keyword	Value
Telescope diameter	8 m
D/r_0	40
Wind velocity	$20\,\mathrm{m\,s^{-1}}$
Wavelength	650 nm
Guide star luminosity	−5 mag
WFS type	Shack Hartmann
Number of WFS lenslets	20 x 20
Number of DM actuators	20 x 20
Frequency	500 Hz

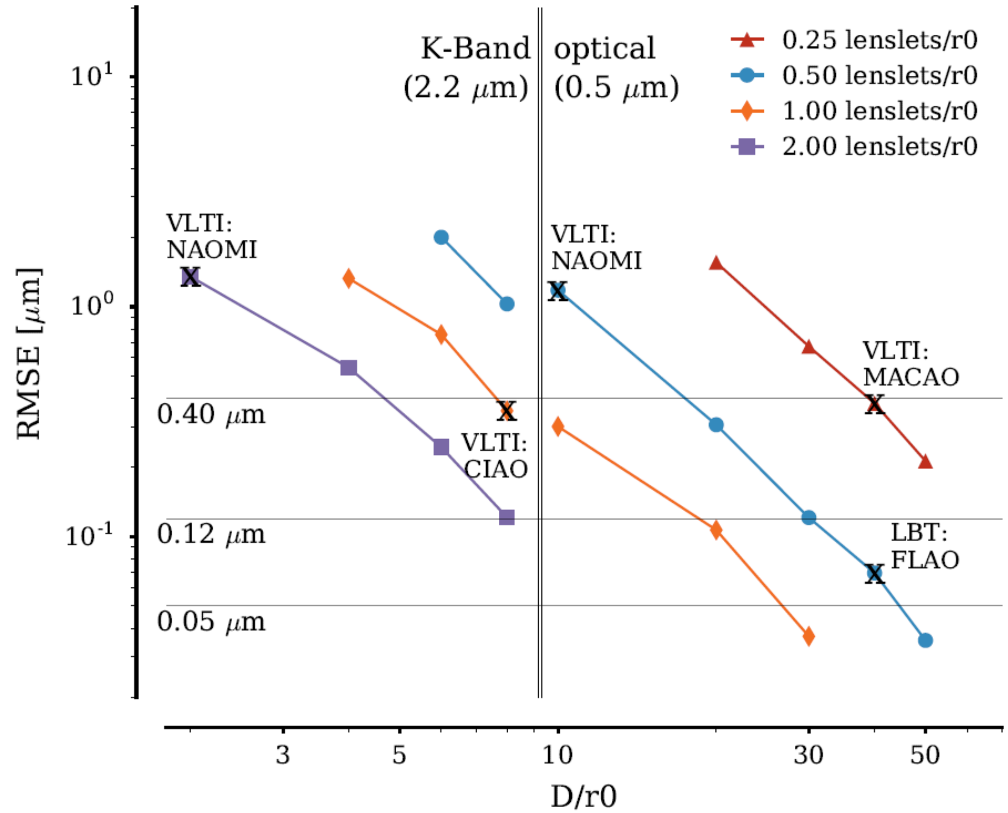


Figure 4. P-REx performance for a varying D/r_0 and different samplings of the WFS. The plot shows results in the K-Band (left part) and in the optical (right part). The different samplings per r_0 are shown in different colors, as indicated in the legend. The gray lines are the same error regimes as before.

- Use of realistic atmosphere (9 Layers, 65% in Ground layer, wind angle of $\pm$ 20°)
- Results decrease but not unusable
- Main error due to wind measurement ($\rightarrow$ larger wind average)

AO system	Single or multilayer	Wind measurement $\mathrm{m\,s^{-1}}$	RMSE μm
SCAO	single	9.56 ± 0.45	0.066
	multi	9.42 ± 0.85	0.426
GLAO	multi	9.41 ± 0.63	0.195

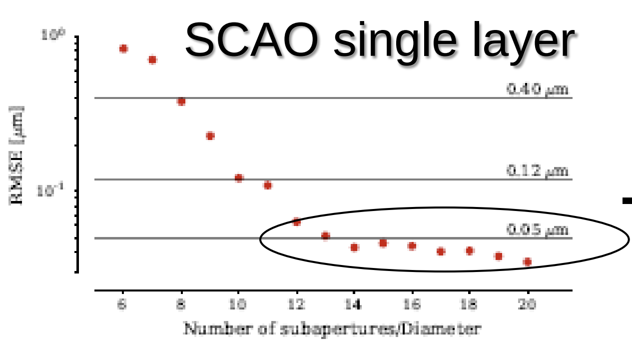
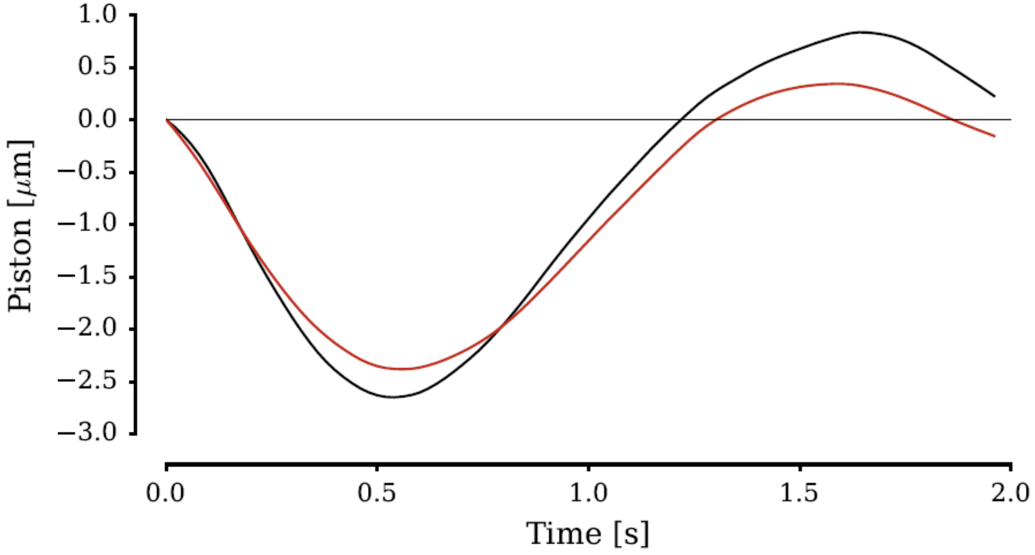


Figure 3. Dependency of the piston reconstruction on the spatial sampling. The plot shows the RMSE dependent on the number of WFS measurements in one telescope diameter. The gray lines indicate the three error regimes as discussed in the text.

- Improving result with a GLAO system (example ARGOS)

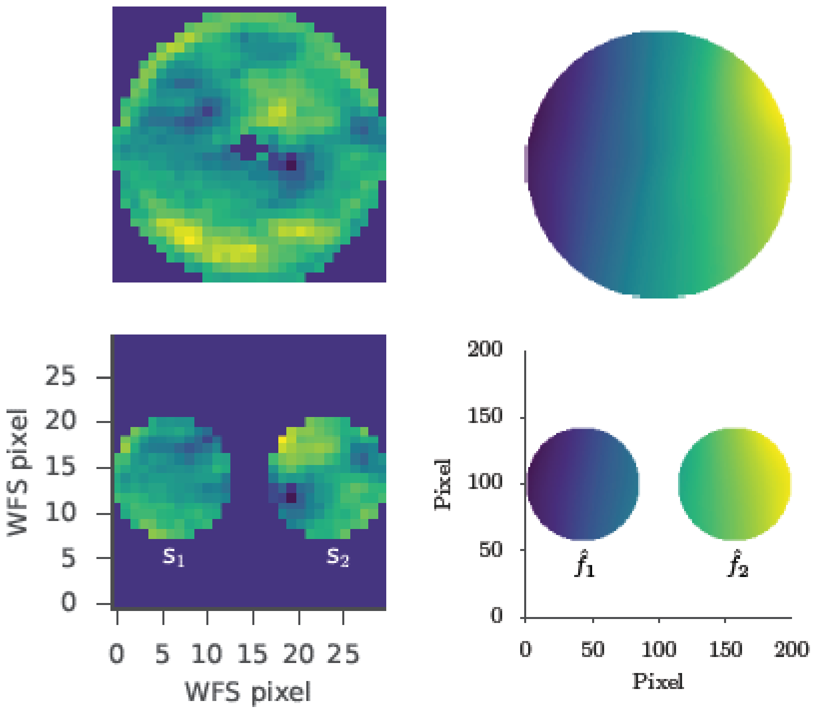


Results from end-to-end simulations

- Piston reconstruction could work under real conditions
  - Simulations did not reveal fundamental show stoppers
  - Except of boiling or particular atmospheric behaviours we simulated realistic multi-layer atmospheres, and WFS performances

- What makes P-REx work
  - The information needed is relatively low-order: if the AO system works, P-REx has enough photons, if the AO system does not work, well then there is no hope anyway
  - Most turbulence is in the ground layer, with a dominant wind speed
    - P-REx approximations are valid

Test P-REx concepts on sky with LBT/FLAO



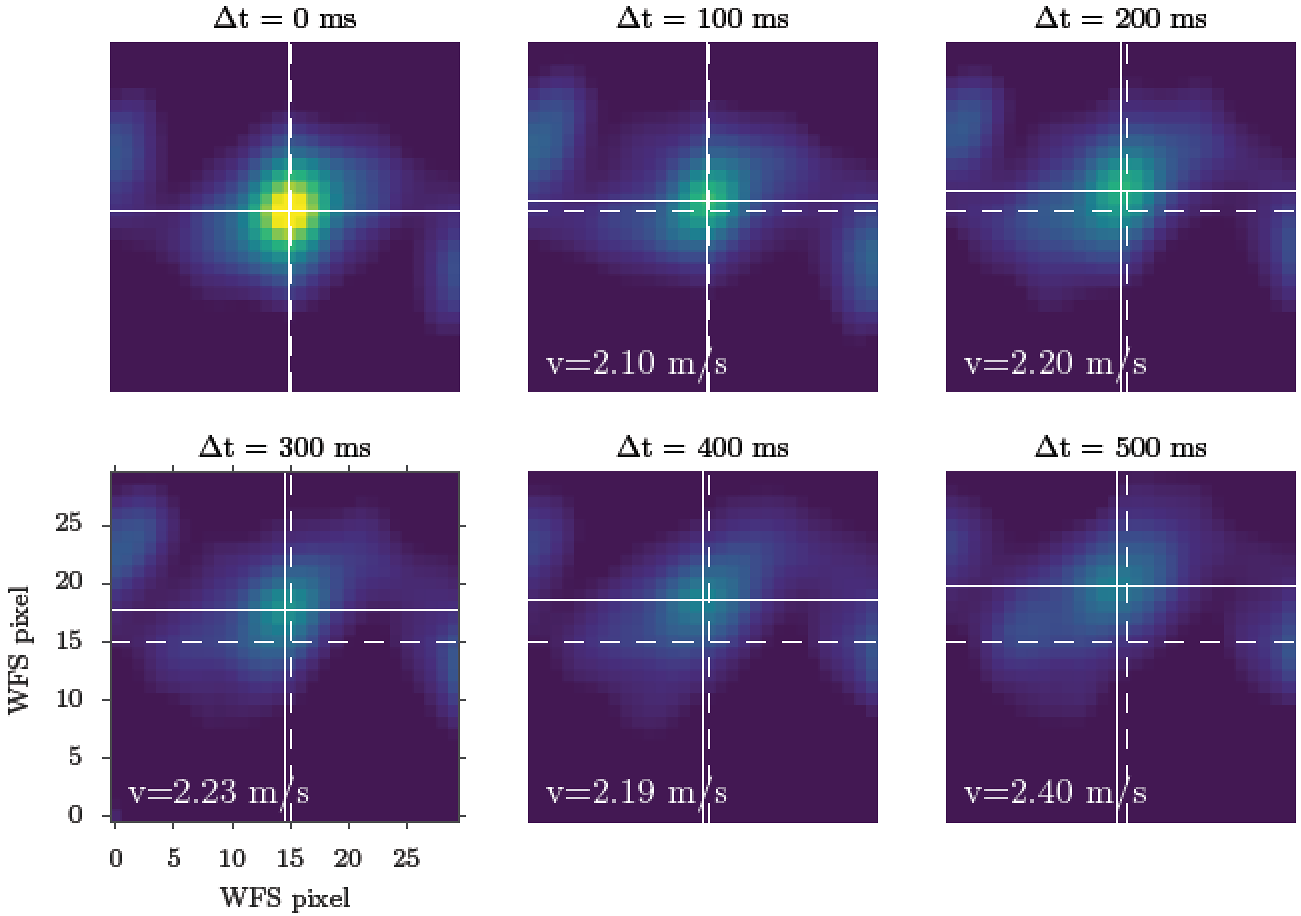
Compare evolution of piston difference of two subapertures from:

- Slope data (P-REx)
- reconstructed wavefront

LBT FLAO data:

- 2 night from 2012
- 21 Data sets of 4 seconds
- Good and medium conditions (seeing $\sim$ 0.5” & 0.9”)
- optional use of more datasets

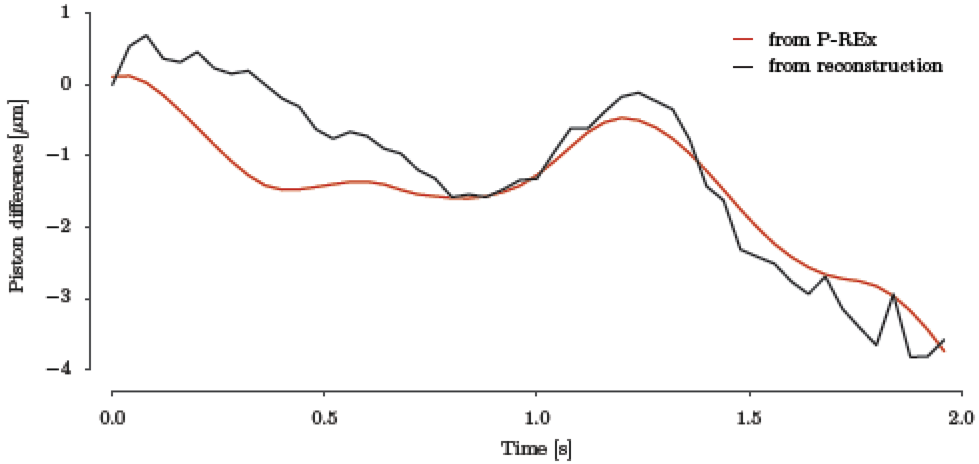
Wind detection from FLAO Data:



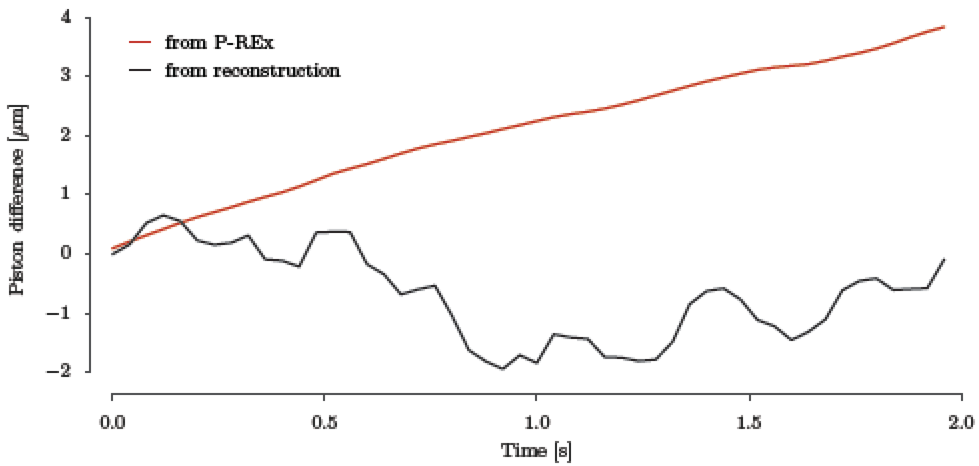
- Works as in our YAO simulations!

Examples for the results:

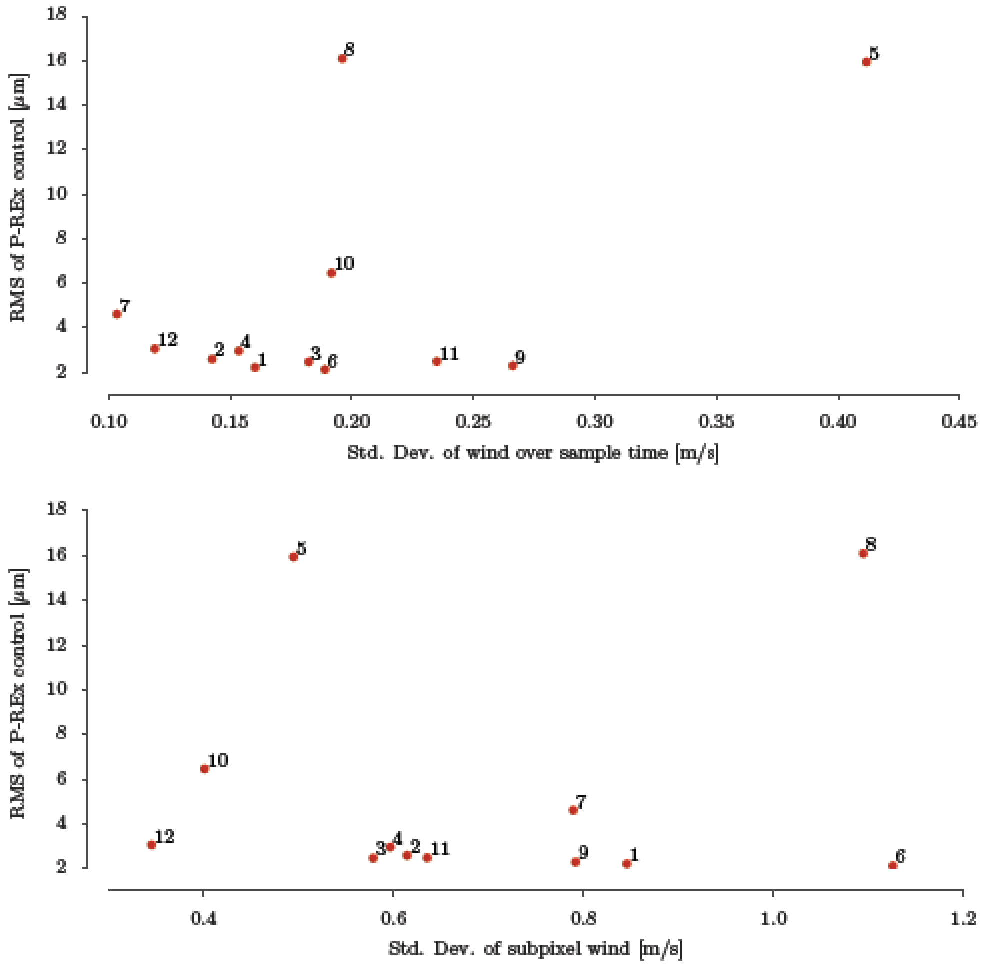
70% of time



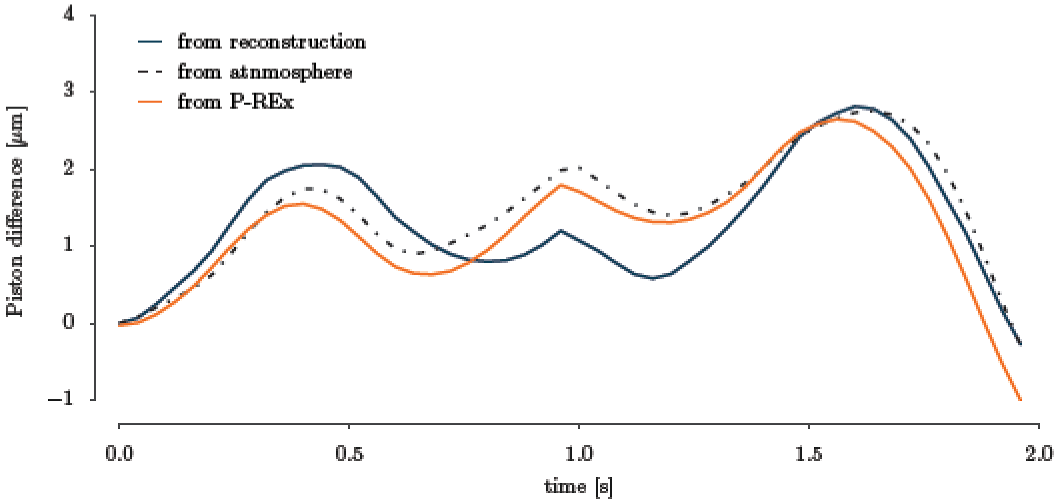
30% of time

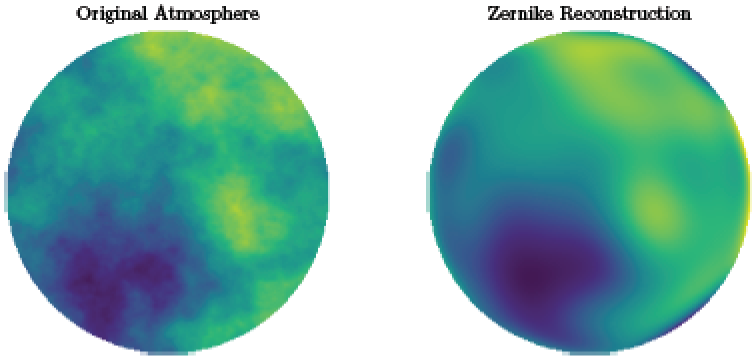


Bad results due to wind variations?



Analysis for simulation data (Pyramid sensor, single layer atmosphere, D/r_0=40) $\rightarrow$ RMS 0.8μm





Test underestimates performance!

4.5 Conclusion from LBT data

The tests with the single aperture method on LBT data largely confirm the results from the simulations. The main results from this part are the following:

- A wind vector is clearly detectable in all the datasets, which is a prerequisite for the success of P-REx.
- The boiling intensity and timescale in these data are similar to previous studies. The found timescales confirm that boiling has only little impact on the P-REx performance.
- The performance of the piston drift reconstruction is similar to the expectations from simulations. This suggests that the main assumptions in the simulations were valid and approves the results from simulations. One can therefore assume that the P-REx results for a full aperture of an 8 m class interferometer are significantly better than for the here presented single aperture tests with the two small subregions.
- The P-REx tests on the FLAO data with good atmospheric conditions give mixed results for one third of the datasets. For the other two thirds, P-REx delivers an OPD RMSE below 3 µm.
- The tests showed that a varying wind vector and bad atmospheric conditions negatively influence the quality of the P-REx results, as it can be expected.

The most important points to take away from the tests on a single aperture are, that the atmosphere is, under good observing conditions, sufficiently well structured, stable and ground-layer dominated, in order to precisely measure an effective wind vector and apply the piston reconstruction algorithm. This leads to a principal beneficial usability of the P-REx algorithms for interferometric observations of faint targets.

Stay tuned for the Paper
Widmann 2017 subm…

Outlook

- LBT/FLAO tests were encouraging, but underestimating the performance (due to phase reconstruction errors, and small sub-apertures used)
- Getting real-time AO vs fringe datasets
  - 1-2 micron residuals over timescales of seconds should be achievable, maybe more

- -> co-phasing for sensitive Matisse MN-band imaging
- -> co-herencing for HKL and even visible (iVis)
- -> improve sensitivity and performance of GravityFT, as test case for high-contrast measurements with Hi5?
  - NSC requirements for not-perfectly stable Null?

- -> lucky interferometric imaging with LBT/LINC
- …

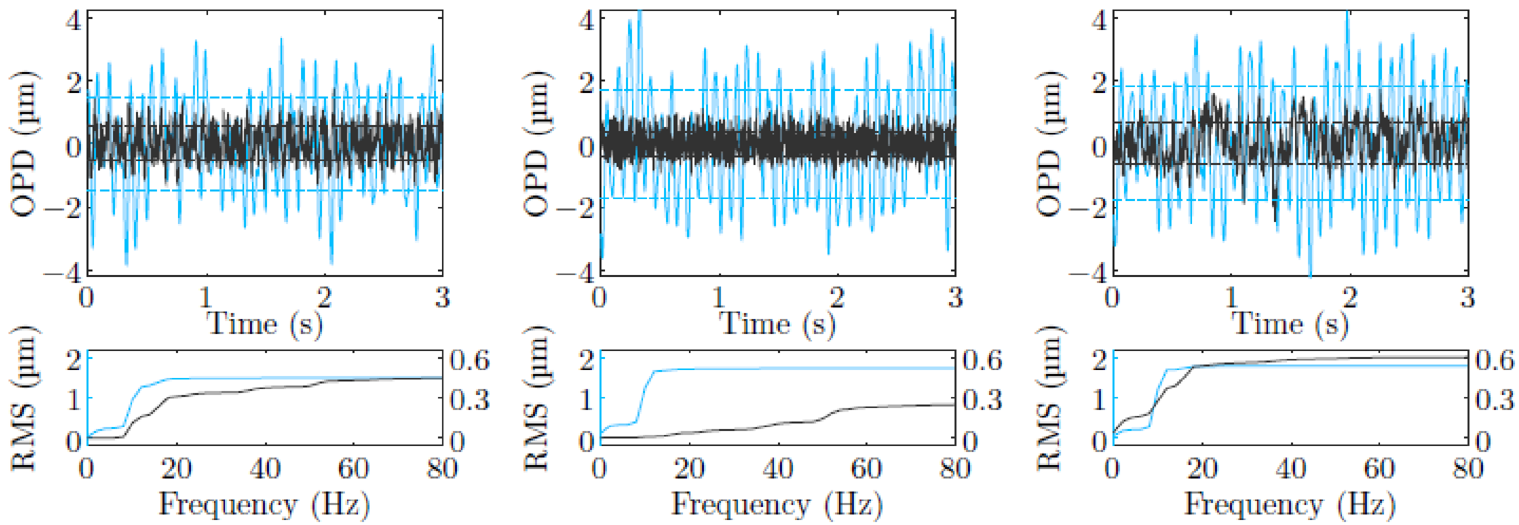
PREx schedule

- 2017: Realistic simulations
    - Done (next slides)
- 2018: On-sky performance tests with LBT; complete algorithm developments
    - Under way (next slides, first data these days)
- 2019: Develop P-REx implementation plan at VLTI
    - Exchange ideas with Gra4MAT project, CIAO+GravFT is ideal
- 2020: Performance support of Matisse fringe tracking operation

- Goals:
    - Coherencing (residual phase jitter < 10..20µm): would allow for very long exposure visibility and closure phase measurements for all VLTI instruments
    - Cophasing for Matisse (residual phase jitter < 1µm): long coherent integrations, in particular for L-M band spectroscopy
    - Complement ESO effort towards VLTI facility fringe tracking

P-REx control implementation

- Feedforward signal (measured outside of fringe loop) onto the delay actuator, just like LBT/OVMS+piston (Boehm+16):



(a) OVMS$^+$ OFF, $K_i = 300$ (b) OVMS$^+$ ON, $K_i = 300$ (c) OVMS$^+$ ON, $K_i = 30$

Figure 6: Time series and cumulated power spectrum of the estimated OPD (blue) and the closed loop residual error (black). Note the two different scales in the spectrum plots for better comparison, with the left axis showing the spectrum of the estimated OPD, and the right axis that of the residual OPD. On the left, there is pure feedback action, in the middle a combination of feedback and disturbance feedforward is used. On the right, the feedback integral gain is reduced by a factor of 10. Without OVMS$^+$ feedforward, the RMS (shown as dashed lines) is reduced from 1489 nm to 539 nm (-64 %), while with OVMS$^+$ feedforward the OPD residual is reduced from 1724 nm down to 403 nm (-77 %). Thus, the combination of both reduces the input disturbance RMS by about a factor of 4.5. Using OVMS$^+$ feedforward, but a much smaller feedback gain restores the performance of the original pure feedback system with a reduction from 1793 nm to 651 nm (-64 %).

- Details, algorithms, performances etc. are still under heavy development
- P-REx cannot deliver high-performance fringe-tracking alone, but supports, and improves the fringe tracking performance
- P-REx can allow to eventually bring the full benefit in terms of sky coverage of LGS-AO to interferometry
  - PFI: combine cheap narrow-field spherical primaries with cheap Rayleigh GLAO/LTAO should work up to 4m class
- Questions?